The Brunswick School Athletic Building

Greenwich, Connecticut

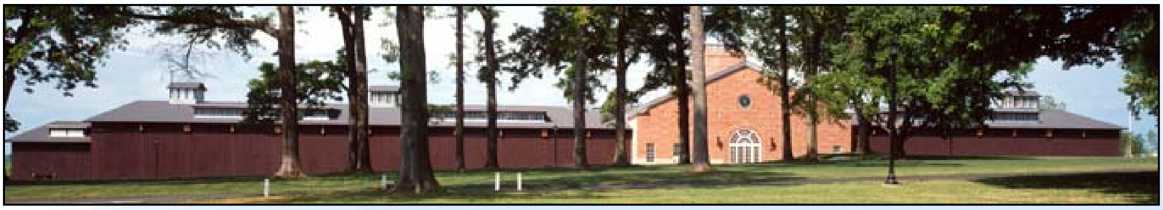
The Pennsylvania State University
Architectural Engineering Thesis

Spring 2003

Kelly J. Doyle
Structural Option

The Brunswick School Athletic Building

Greenwich, Connecticut



Kelly J. Doyle *Penn State University* *Structural Option*

Owner
The Brunswick School
100 Maher Avenue
Greenwich, Connecticut

Contractor
Turner Construction
Greenwich, Connecticut

Architects
Skidmore, Owings & Merrill, LLP
New York, New York

Structural Engineers
Gilsanz Murray Steficek, LLP
New York, New York

Civil Engineers
Redniss & Mead, Inc.
Stamford, Connecticut

Geotechnical Engineers
EarthTech
Glastonbury, Connecticut

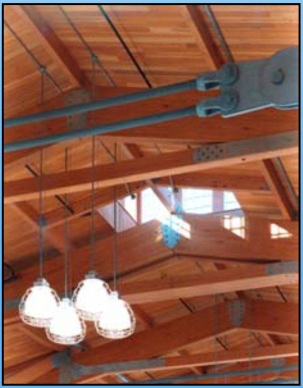
Mechanical / Electrical Engineers
Atkinson Koven-Feinburg
New York, New York

Features

- **65,500 square feet**
- **Mirrors "shaker-style" barns & houses of classic Connecticut architecture**
- **NCAA regulation-size ice hockey rink & basketball court**
- **3-story center core with weight room, squash courts, & locker rooms**

Structural

- **105' clear span timber glulam roof trusses**
- **Steel cable roof supports**
- **24' masonry walls**
- **Large sliding doors for zamboni machine**
- **Core floor of pre-cast planks**



Electrical/Lighting

- **400 watt Prismaline fixtures over sport floors**
- **Covered with protection from flying balls & pucks**

Mechanical

- **147 cold pipe circuits & 21 hot circuits in hockey floor**
- **Dehumidification unit**
- **Dry sprinkler system above frozen floor, wet system elsewhere**

All photos from www.som.com.

Executive Summary

The following report is a summary of thesis research into the design of the Brunswick School Athletic Building. This building is split into three major sections: an ice hockey rink, a basketball court and a three-story central "brain" which houses a weight room, locker rooms, offices and squash courts. The design and construction teams included Skidmore, Owings & Merrill (SOM), Gilsanz Murray Steficek (GMS) and Turner Construction and was completed in late summer 2000. The design was developed to resemble the "shaker-style" barns and houses of Connecticut. All proposed redesign aimed to retain this style of architecture.

The existing structure consists of fully-grouted CMU walls with 105' span glulam timber trusses, designed and fabricated by Unadilla Laminated Products, spaced at 30'-35' bearing on concrete piers within the walls. The trusses have a steel bottom chord to aid in carrying tension loads. In the brain section, the floor system consists of pre-cast concrete planks on load-bearing masonry walls. The roofing system is made up of asphalt shingles on cedar plywood and rigid foam insulation bearing on purlins framed into the trusses. The CMU walls are covered with cedar siding on cedar plywood and rigid insulation or stone over rigid insulation. The building foundation consists of large concrete footings under each pier as well as a footing at the base of all walls.

Reviewing the design of many other long span roofs over swimming pools, ice rinks or similar spaces revealed that an arched frame is often used to support the roof and the walls. A Tudor arch design would allow the roof framing to be finished earlier in the building construction, rather than waiting for the walls to be finished. Piers would no longer be needed within the walls. This report contains analysis of a glulam timber arched frame which retains the "barn" feel of the building. Unadilla is a frequent designer, manufacturer and supplier of similar glulam members and should be contracted to building the Tudor arches as well.

The American Institute of Timber Construction specifies sizes of frames similar to the one to be analyzed in design charts. Wind, seismic, snow and dead loads were applied to the proposed frame using an excel spreadsheet. Minimum base and peak sizes were kept near 3' and deflection criteria was monitored. Based on these requirements, frames at the existing spacing needed to be too very deep to withstand imposed stresses. A new spacing of 20-22 feet as reviewed, and these frames performed successfully.

Based on new dead loads with timber frames rather than timber trusses and concrete piers, frame total weights were reviewed, but due to spacing requirements the comparison has little effect on final recommendations. A refined construction schedule shows the

skimming of nearly three months off the total time, ideal for a school working around arrival times for students.

In addition to research into structural revisions, this report will review the performance of the building envelope. The quality of the walls' resistance to heat flow, water vapor flow, water penetration, CMU shrinkage and thermal expansion were investigated. Thermal and vapor gradients will be developed, and locations of expansion joints, moisture barriers, insulation and flashing were reviewed. Interior conditions in both the ice rink and basketball court were countered with exterior summer and winter conditions for Greenwich, Connecticut. Exterior conditions were determined by visiting Accuweather.com, while interior conditions, material performance values for thermal expansion, heat flow resistance and vapor resistance will be gathered from *ASHRAE Fundamentals* and *ASHRAE Fundamentals*. The research showed that despite the extreme variation in interior conditions of the ice rink and basketball court, the ice rink wall accumulated water, but in a layer of the wall that facilitated drainage.

In the following report, lighting conditions in the ice rink were successfully improved. The present light fixture layout induces bright spots of concentrated light on the ice surface; such spots can distract players causing dangerous playing conditions. The new layout accommodates the reduction in roof support spacing, spreads out the fixtures and offers a much more evenly lit surface.

Table of Contents

Tables & Figures

Building Background

Construction & Use

The Brunswick School Athletic Building was built as part of Phase I of the newly opened Edwards Middle School Campus of the boys' college preparatory school in Greenwich, Connecticut. The winter sports complex was completed in time for the Fall 2000 semester, taking approximately 17-18 months and costing roughly $11 million to build. The entire Phase I project, including an academic building and site work for the 104 acre campus, was designed and built by the following firms:

Architects:	Skidmore, Owings & Merrill, LLP	New York, NY
Structural Engineers:	Gilsanz Murray Steficek, LLP	New York, NY
MEP Engineers:	Atkinson Koven-Feinburg	New York, NY
Construction Management:	Turner Construction Company	Greenwich, CT
Roof Truss Contractors:	Unadilla Laminated Products	Unadilla, NY
Ice Hockey Rink Design-Build:	American Refrigeration Company, Inc.	Woburn, MA

Table 1. Project Team.

The 65,500 square foot facility houses an NCAA regulation-size ice hockey rink, an NCAA regulation-size basketball court, 8 international size squash courts, a weight room, locker rooms, and offices. The building is divided into three major sections: the rink, the "brain" and the court. The location of these sections can be seen in Figure 1, the first floor plan. The rink and court have 29 foot high walls and 105 foot roof span, as shown section in Figure 2. The brain between them is three stories, visible in section in Figure 3, is where the locker rooms, squash courts and offices are located.

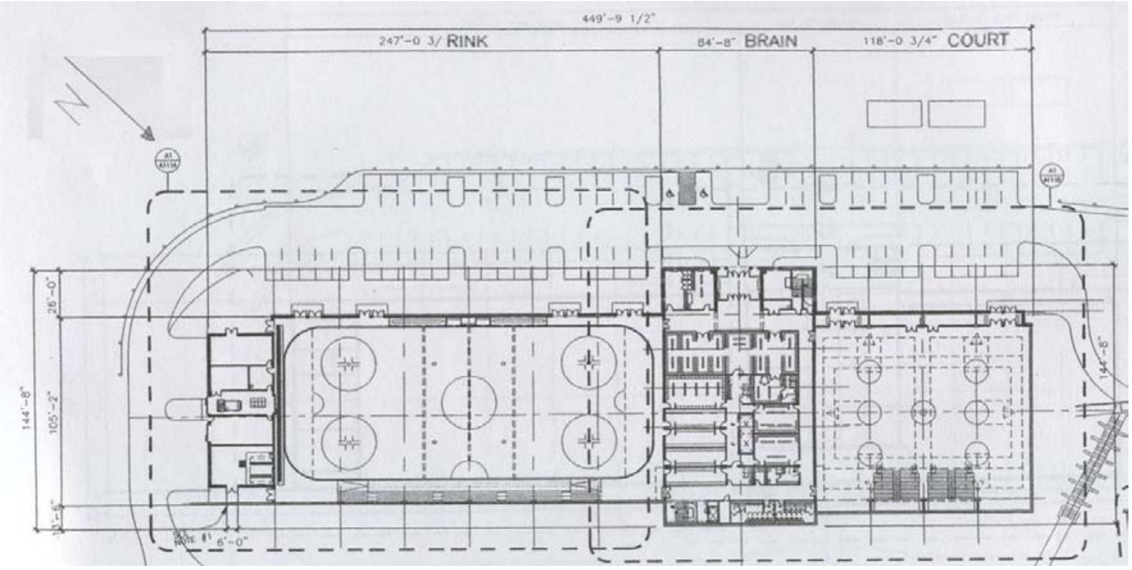


Figure 1. First floor plan; rink, brain and court labeled left to right.

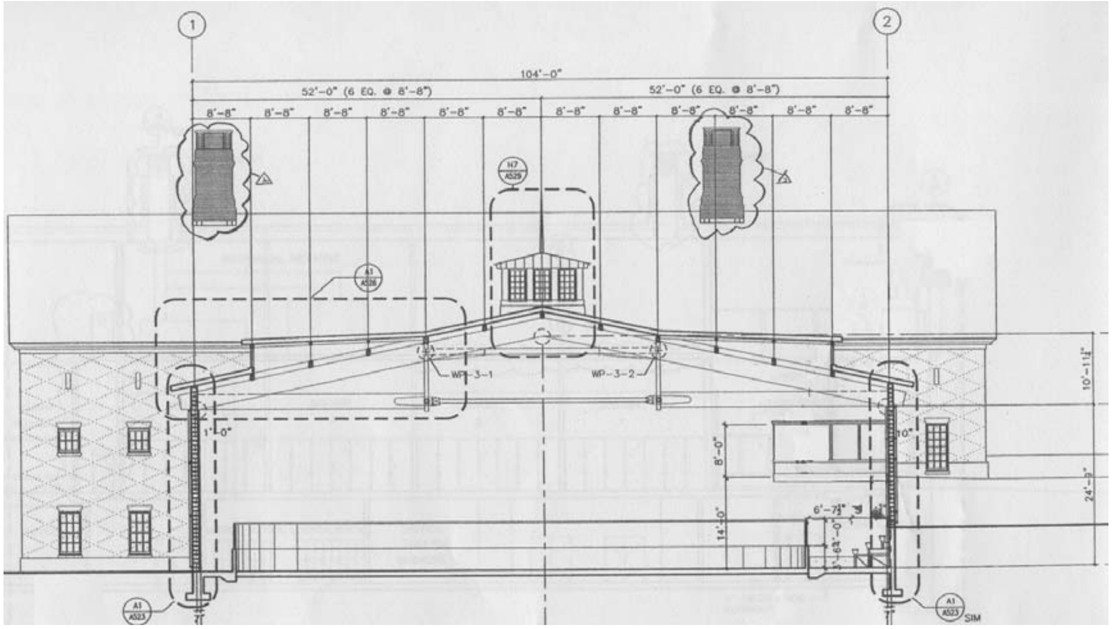


Figure 2. Building section through rink; shows truss shape.

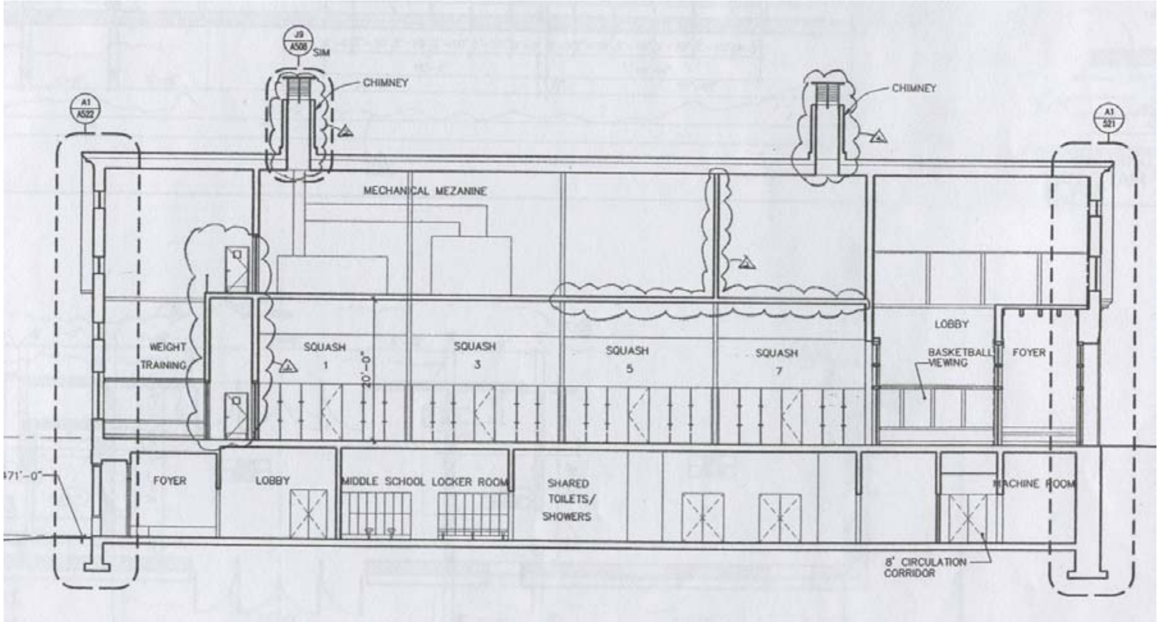


Figure 3. Building section through 3-story "brain."

The overall design of the building was selected to reflect the “shaker-style” Connecticut architecture of local barns and houses. The Shakers built their homes and gathering places with large open spaces, gabled roofs and high ceilings. They were found of simple, yet stunning architectural styles. Many photos of traditional buildings show one or two chimneys, or a cupola. Small dormer windows were used occasionally but not as consistently as chimneys and cupolas. An example of Shaker Architecture is shown in Figure 4.

Figure 4. Cow Barn at Alfred Shaker village, includes cupola. Credit: National Park Service.

Structural Systems

All exterior walls to the athletic building are fully grouted concrete masonry. The south wall of the ice rink is 10” block with minimum #5@24” rebar, and all other walls are 12” block with minimum #6@24” rebar. Horizontal reinforcement consists of 2-#9 bars at 16”. Any parts of walls located below grade, such as the first 8-10 feet of the rink’s south wall, are cast-in-place concrete retaining wall. The walls are interrupted by solid 36”x 16” (36”x 14” on 10” block walls) concrete piers spaced 30’-35’. Control joints in the masonry walls are located at each set-back corner, as shown in Figure 5, and at each pier. The walls and piers are fully braced at their base by dowels poured with the footings. The footings under each pier are as large as 7’ x 7’ and footings bear on very rigid soil. The concrete block is covered with rigid insulation and cedar plywood, or rigid insulation and stone, also visible in Figure 5. All CMU walls are left exposed in the interior spaces but have a brown tint which can be seen in Figure 6 from Skidmore, Owings & Merrill’s (SOM) website.

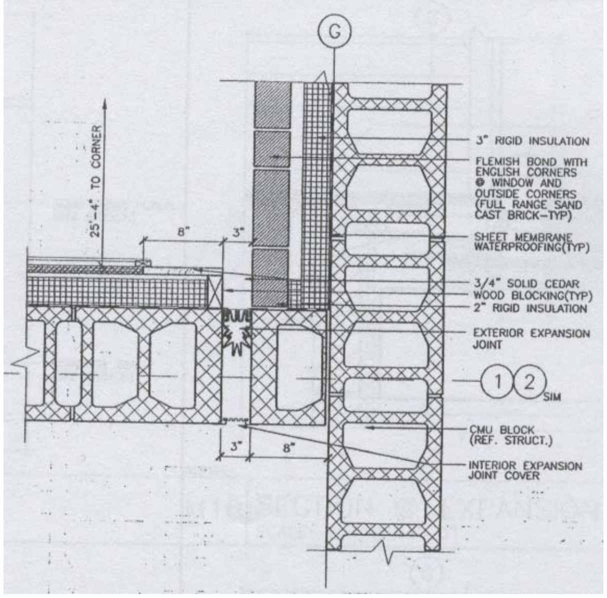


Figure 5. Detail at re-entrant corner showing control joint and enclosure materials.

Walls within the center “brain” of the building are load-bearing fully-grouted 8”, 10” or 12” block. The fully grouted masonry aids significantly in fulfilling the Brunswick School’s wishes to buffer the interior of the building from the noise of the nearby Westchester Airport. The third floor, the mechanical mezzanine, consists of 4” concrete on metal deck, supported by wide-flange steel beams spanning 21’-9”. These beams rest on W12 and TS12 columns that pass down to CMU walls on the first floor. The second floor is built of hollow pre-cast concrete planks of various thicknesses, bearing into CMU walls and wide-flange beams spanning any doorways or other openings.

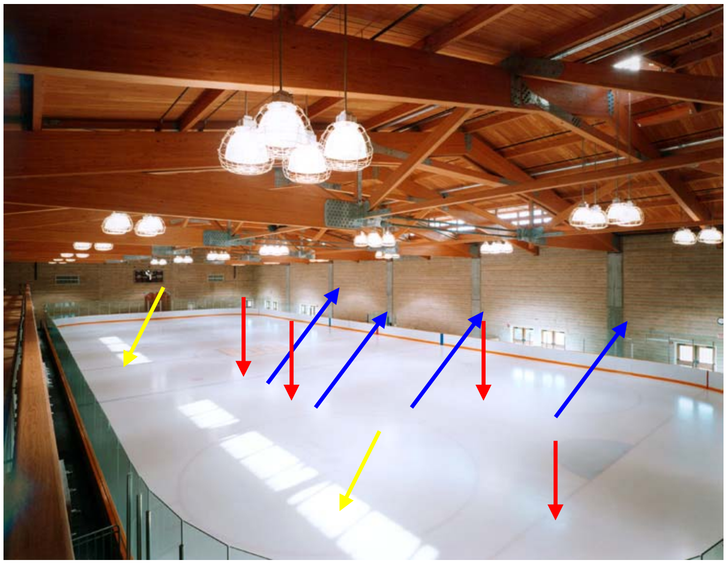


Figure 6. Ice rink; Piers marked with BLUE arrows; light from dormers marked with YELLOW arrows; bright spots from light fixtures shown with RED arrows; Photo Credit: www.som.com.

The first floor of the entire building is slab-on grade concrete. Floor surfaces are unique to each space: insulation, additional concrete and two layers of pipe for the ice surface; carpet in offices; tile in locker rooms; and a sports surface floor for basketball.

The roof of the Brunswick School Athletic Building is constructed of glulam timber trusses with glulam purlins, cedar plywood and asphalt shingles. Over the rink and basketball court, the clear span of the trusses is approximately 105' and are spaced 30'-35' apart, bearing on the concrete piers within the block walls. The top chords of a representative truss is 8 ½" x 33"; the bottom chord is 6 ¾"x 30 ¼" glulam spliced with a steel cable for the middle 1/3 of the chord to resist the high tension forces. The building section in Figure 2 shows the shape of the truss. Also visible in that building section are the decorative cupolas and dormer windows on the roofs of the rink and court.

According to UBC 2000, buildings in Greenwich, Connecticut should be designed for 30 psf of snow and 80 mph winds. For wind and seismic calculations, this building has an importance factor of 1.23-1.25 because it is considered an education facility. The building is located in seismic zone 2A.

All steel complies with ASTM A572 Grade 50 (f_y = 50 ksi). All masonry has a maximum compressive strength of 2000 psi; mortar is type S; masonry reinforcement is Grade 60. All cast-in-place concrete was specified to be 4000 psi, normal weight, with Grade 60 reinforcing bar.

Lighting, Mechanical & Fire Protection

Recessed fluorescent lights hang above most spaces in the facility. 400 watt Prismaline fixtures are suspended in clusters of two above the basketball court and in clusters of four above the hockey rink. These fixtures, as well as those above the squash courts, are covered with guards to prevent damage from balls and pucks.

Like any athletic building, with showers and sweaty players, in addition to a few hundred square feet of ice and the equipment needed to maintain the ice, this building has potential for very high interior relative humidities. To prevent mass quantities of condensation on any and all surfaces, the third floor mechanical mezzanine is home to a 13,000 cfm desiccant dehumidification unit. The unit, described in the HVAC schedule as similar to a Munters Drycool, is capable of removing 148 pounds of water from the air every hour.

The athletic building is protected from fire damage by an extensive sprinkler system in accordance with the NFPA and Connecticut Building Code. Dry sprinkler systems are used in any building areas subject to freezing temperatures, such as above the ice hockey surface and the adjoining ice and zamboni maintenance rooms. Wet systems are used to protect all other spaces. As with light fixtures, the sprinkler heads above the hockey rink, squash courts and basketball court are covered with protective guards to defend against flying pucks and balls. The large timber trusses do not need fireproofing because of timber's ability to last in fire. Once the wood is charred, the flames cannot penetrate further, allowing large timbers to last longer than steel framing and retain most of their strength longer. The steel cables in the truss bottom chords are not coated with fireproofing, but at over 25 feet above the floor are relatively safe from flame and protected from heat by the sprinkler system.

Structural Design

Design Goals

Reviews of Unadilla Laminated Products' website, www.unalam.com, and the American Institute of Timber Construction's website, www.aitc-glulam.org, spurred the initial review of a glulam frame system. The AITC refers to such frames as Tudor arches or three-hinged arches. Many buildings housing ice rinks, gymnasiums, swimming pools and other similarly large spaces have roofs framed with glulam timber framing without actual trusses.

Other alternatives were reviewed for redesign of the roof of the Athletic Building. They include steel trusses, steel bar joists and steel Tudor arches. These designs were discarded because, although potentially cheaper, they conflicted with the desire to maintain the Shaker barn style reflected in the rest of the Edwards Campus.

The overall building dimensions, 29' walls, 105' roof spans and 43' roof peak height from floor, are maintained. The arches were initially designed at the same 30-35' spacing that the existing trusses utilize, but deflection criteria required adjusting the spacing to 20-22 feet to maintain reasonable member depths.

Two main criteria will be used to compare the new frames to the existing trusses: architectural integrity and construction time. Weight on the foundation will be compared but is very similar to that of the initial framing, and changing the spacing negates this comparison. Initial and final costs will not be compared because of the belief that cost was not a factor in the design of the Brunswick School Athletic Building. Initial estimates with glulam arches for an athletic building, according to RS Means, start from a basis of approximately $92 per square foot. A much cheaper version with steel bar joists would have a base cost of $82 per square foot; over 65,500 square feet, the difference of $655,000, in addition to the high quality ice rink and other fixtures selected suggests that cost was not a decision criteria for the Brunswick School.

Design Method

The American Institute of Timber Construction (AITC) details the design methods for a glulam Tudor arch in *AITC Technical Note 23, Mathematical Solution for the Design of a Three Hinged Arch*.

Based on recommendations from Jeff Linville, Technical Manager at AITC, a very available grade of glulam was selected, 24F-V5 SP. Southern Pine lumber was selected because it is more readily available in the Eastern United States, as opposed to Douglas Fir which is more widely used in the West. This grade of glulam is specified to have the following strength values from *AITC 117-2001 – Design, Standard Specifications for*

Structural Glued Laminated Timber of Softwood Species and coefficients from the *National Design Specifications for Wood Construction* (NDS):

Grade 24F-V5 SP		AITC 117-2001 Table 1
Fb =	2400	psi
Fc =	1650	psi
Fc⊥ =	740	psi
Fv =	240	psi
Ex =	1700000	psi
Ey =	1500000	psi

Table 2. Glulam specifications.

Adjustment Values			Fb	Fc	Fc⊥	Fv	Ex	Ey
Wet Service	Cm	T=50, RH=60, MC=11.2%>16%	1	1	1	1	1	1
Load Duration	Cd	Wind Load	1.6	1.6	1.6	1.6	X	X
		Snow Load	1.15	1.15	1.15	1.15	X	X
Temperature	Ct	T=50	1	1	1	1	1	1
Volume	Cv	$\left(\frac{5.125}{b}\right)^{\frac{1}{20}}\left(\frac{12}{d}\right)^{\frac{1}{20}}\left(\frac{21}{L}\right)^{\frac{1}{20}} \leq 1.0$	tbd	X	X	X	X	X
Beam Stability	C_L		to be determined as needed				X	X
Curvature	Cc	$1 - 2000\left(\frac{t}{R}\right)^2$	0.91	X	X	X	X	X

Table 3. Glulam strength coefficients.

Loadings for full balanced snow load, drifted snow load and wind load. Assumptions were made to distribute wind load between the CMU walls and the timber frames. It was conservatively estimated that the walls would transfer one half of the lateral load to the foundation and the other half to the frames. Seismic loads are applied when calculating base shear. Dead loads for the actual frame are accounted for in the strength values in *AITC 117-2001*.

An Excel spreadsheet was developed based on the mathematical solution to find the geometry of the arch, forces at sample sections, stresses at these sections and deflection values. Calculations begin with sizing of the base due to the largest shear loads, and continue up the member using geometric and trigonometric computations. Alterations were made to the given formulas to account for the point load of a cupola on the roof on some frames. Deflection was calculated using the virtual work method. Radial tension was also checked. The use of a spreadsheet aided in design for quick changes in spacing and loading patterns. For most cases, critical loading occurred under unbalanced snow load and wind, but occasionally higher shears occurred without wind load. Excerpts from calculations of loading, stress and deflection follow in Figure 7 for the 20'-0" spacing in the basketball court.

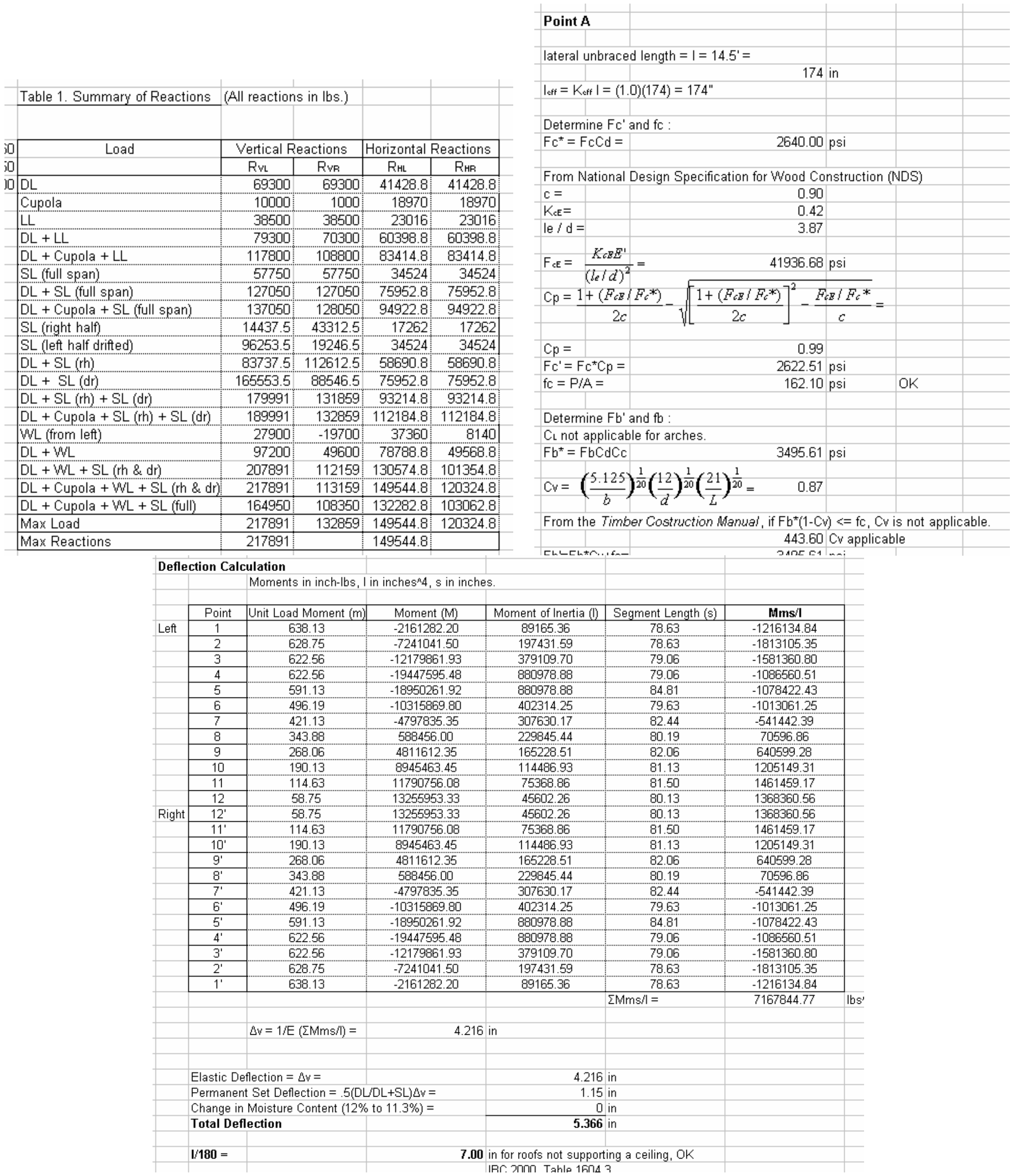


Table 1. Summary of Reactions (All reactions in lbs.)

Load	Vertical Reactions		Horizontal Reactions	
	R_{VL}	R_{VR}	R_{HL}	R_{HR}
DL	69300	69300	41428.8	41428.8
Cupola	10000	1000	18970	18970
LL	38500	38500	23016	23016
DL + LL	79300	70300	60398.8	60398.8
DL + Cupola + LL	117800	108800	83414.8	83414.8
SL (full span)	57750	57750	34524	34524
DL + SL (full span)	127050	127050	75952.8	75952.8
DL + Cupola + SL (full span)	137050	128050	94922.8	94922.8
SL (right half)	14437.5	43312.5	17262	17262
SL (left half drifted)	96253.5	19246.5	34524	34524
DL + SL (rh)	83737.5	112612.5	58690.8	58690.8
DL + SL (dr)	165553.5	88546.5	75952.8	75952.8
DL + SL (rh) + SL (dr)	179991	131859	93214.8	93214.8
DL + Cupola + SL (rh) + SL (dr)	189991	132859	112184.8	112184.8
WL (from left)	27900	-19700	37360	8140
DL + WL	97200	49600	78788.8	49568.8
DL + WL + SL (rh & dr)	207891	112159	130574.8	101354.8
DL + Cupola + WL + SL (rh & dr)	217891	113159	149544.8	120324.8
DL + Cupola + WL + SL (full)	164950	108350	132282.8	103062.8
Max Load	217891	132859	149544.8	120324.8
Max Reactions	217891		149544.8	

Point A

lateral unbraced length = l = 14.5' =
174 in

$l_{eff} = K_{eff}\, l$ = (1.0)(174) = 174"

Determine Fc' and fc :

Fc* = FcCd = 2640.00 psi

From National Design Specification for Wood Construction (NDS)

c = 0.90

K_{cE}= 0.42

le / d = 3.87

$$F_{cE} = \frac{K_{cE}E'}{(l_e/d)^2} = \quad 41936.68 \text{ psi}$$

$$C_p = \frac{1+(F_{cE}/F_c^*)}{2c} - \sqrt{\left[\frac{1+(F_{cE}/F_c^*)}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}} =$$

Cp = 0.99

Fc' = Fc*Cp = 2622.51 psi

fc = P/A = 162.10 psi OK

Determine Fb' and fb :

C_L not applicable for arches.

Fb* = FbCdCc 3495.61 psi

$$C_v = \left(\frac{5.125}{b}\right)^{\frac{1}{20}}\left(\frac{12}{d}\right)^{\frac{1}{20}}\left(\frac{21}{L}\right)^{\frac{1}{20}} = \quad 0.87$$

From the *Timber Costruction Manual*, if Fb*(1-Cv) <= fc, Cv is not applicable.

443.60 Cv applicable

Deflection Calculation

Moments in inch-lbs, I in inches^4, s in inches.

	Point	Unit Load Moment (m)	Moment (M)	Moment of Inertia (I)	Segment Length (s)	**Mms/I**
Left	1	638.13	-2161282.20	89165.36	78.63	-1216134.84
	2	628.75	-7241041.50	197431.59	78.63	-1813105.35
	3	622.56	-12179861.93	379109.70	79.06	-1581360.80
	4	622.56	-19447595.48	880978.88	79.06	-1086560.51
	5	591.13	-18950261.92	880978.88	84.81	-1078422.43
	6	496.19	-10315869.80	402314.25	79.63	-1013061.25
	7	421.13	-4797835.35	307630.17	82.44	-541442.39
	8	343.88	588456.00	229845.44	80.19	70596.86
	9	268.06	4811612.35	165228.51	82.06	640599.28
	10	190.13	8945463.45	114486.93	81.13	1205149.31
	11	114.63	11790756.08	75368.86	81.50	1461459.17
	12	58.75	13255953.33	45602.26	80.13	1368360.56
Right	12'	58.75	13255953.33	45602.26	80.13	1368360.56
	11'	114.63	11790756.08	75368.86	81.50	1461459.17
	10'	190.13	8945463.45	114486.93	81.13	1205149.31
	9'	268.06	4811612.35	165228.51	82.06	640599.28
	8'	343.88	588456.00	229845.44	80.19	70596.86
	7'	421.13	-4797835.35	307630.17	82.44	-541442.39
	6'	496.19	-10315869.80	402314.25	79.63	-1013061.25
	5'	591.13	-18950261.92	880978.88	84.81	-1078422.43
	4'	622.56	-19447595.48	880978.88	79.06	-1086560.51
	3'	622.56	-12179861.93	379109.70	79.06	-1581360.80
	2'	628.75	-7241041.50	197431.59	78.63	-1813105.35
	1'	638.13	-2161282.20	89165.36	78.63	-1216134.84
					ΣMms/I =	7167844.77 lbs

Δv = 1/E (ΣMms/I) = 4.216 in

Elastic Deflection = Δv = 4.216 in
Permanent Set Deflection = .5(DL/DL+SL)Δv = 1.15 in
Change in Moisture Content (12% to 11.3%) = 0 in
Total Deflection **5.366** in

l/180 = **7.00** in for roofs not supporting a ceiling, OK
IBC 2000, Table 1604.3

Figure 7. Sample calculations of loads, stresses and deflection.

Based on the fact that the floor plan allows for just over 5 feet between the wall and the ice rink, it was desired to keep the depth of the base and section A close to or under 36". Initial widths of 10 ½ inches were suggested by Mr. Linville because that is the largest size that could be manufactured using one lamination per width. This produced sizes beyond those desired, so the width was increased to 14 inches and the excess manufacturing hassle and cost was acknowledged. The lamination thickness of ¾” as well as width and depth values, were kept within the guidelines of *AITC 113-2001 Standard for Dimensions of Structural Glued Laminated Timber*. The radius of curvature 9’-4” was selected based on minimum values in *AITC 117-2001*.

Allowable stresses were compared to actual stresses at five different sections in the frame. Section depths were increased manually to accommodate slight increases in strength, but large differences were checked, and accepted as member failure. This prompted the reduction of the original frame spacing, 35 ft. The 35 foot spacing divided the ice rink into six sections. An even number of spaces was retained because of the symmetry of the hockey rink.

Deflection values for the peak were compared to $\ell/180$, per UBC 2000 for roofs that do not support a ceiling. Eight and ten spaces were reviewed. Frames over eight spaces required too much depth to maintain strengths, so deflection calculations of these frames were skipped. Ten spaces performed the best, using 21’-4” spacing in the ice rink, 30 inch base depth and a peak deflection of 5.336” inches under full snow load.

Calculation spreadsheets for each frame spacing are included in Appendix A of this report and are summarized in the following table.

Spacing	Base Depth	Peak Depth	Peak Deflection	Lateral Drift
35’-0”	45”	28.5”	Not calculated	Not calculated
21’-4”	36”	31.5”	5.366”	1.35”
20’0”	36”	28.5”	5.11”	1.29”

Table 4. Structural calculation summary.

Figure 8 shows the frame and dimensions for the 20’-0” spaced frame for the basketball court roof. Dimensions vary only slightly for the 21’-4” spaced arch for the ice hockey rink roof.

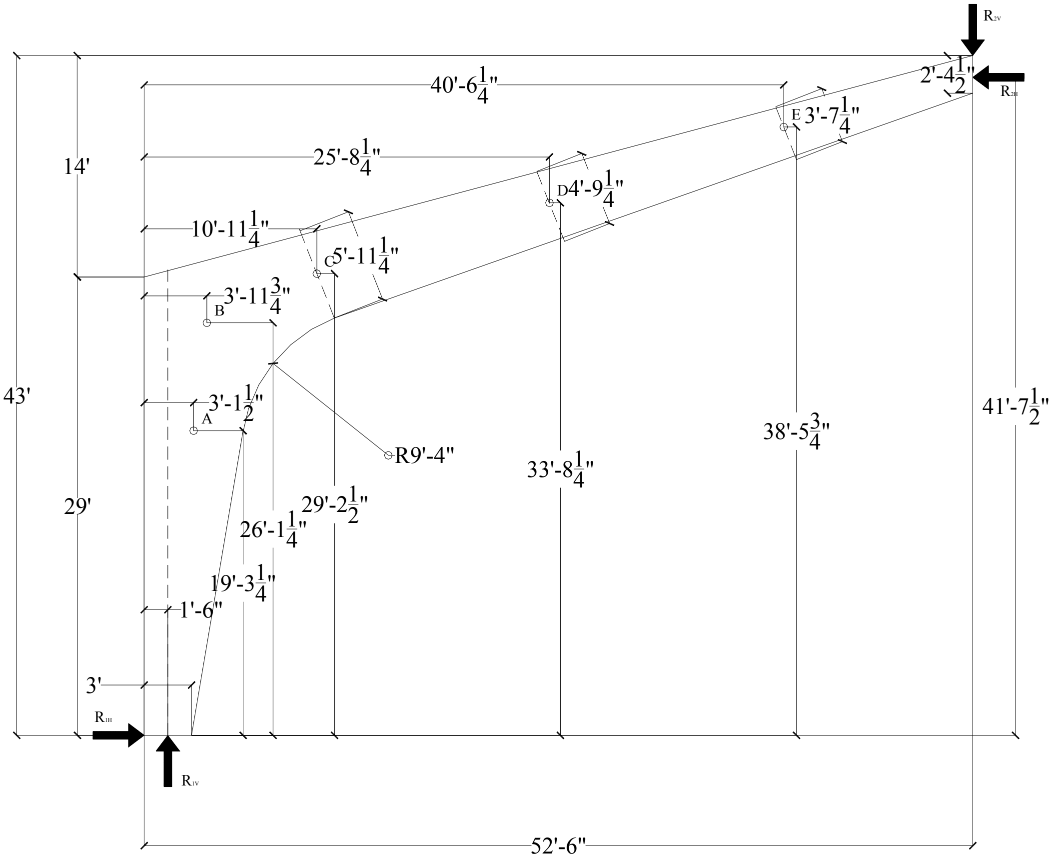


Figure 8. Frame with section dimensions.

Connections

The three-hinged arch is so named because of its pinned connection at each base and at the peak. Wind and seismic loads are transferred to the foundation using shear connections. Each base of an arch is set on a steel bearing plate to elevate it and prevent water absorption. Three steel angles on each side are bolted to the arch and to the concrete as shown in Figure 9. The proper bolt spacing and angle sizes prescribed by NDS are achieved, preventing any possibility of cracking due to thermal or moisture expansion.

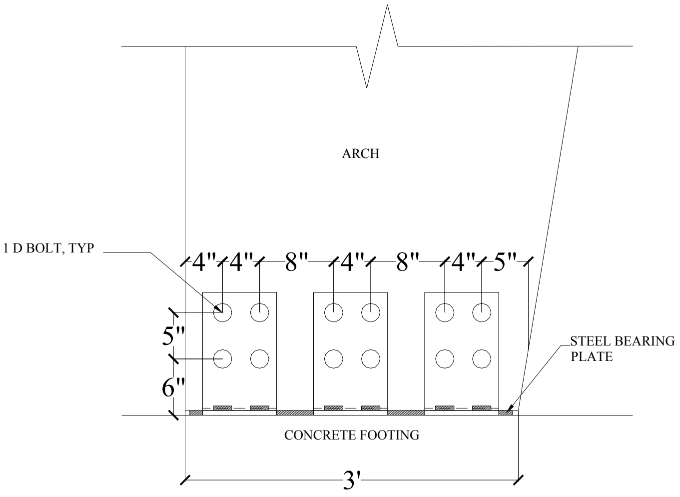


Figure 9. Base connection.

Under uniform load the peak of an arch should be in pure compression, but snow load is often not uniform. To resist this imposed shear, the two sides of each arch are connected at the peak by steel plates bolted to the frame and shear plates on a dowel, as shown in Figure 10. Calculations to determine the number of bolts needed is included in Appendix A.

Figure 10. Peak connection.

System Weight

Calculations of the weight of each system are summarized in the following chart. The concrete piers were assumed to weigh 150 pcf, the masonry walls were listed as 127 pcf in *Design of Reinforced Masonry Structures*, and Southern Pine was calculated to have a weight of 34.3 pcf. Weight calculations can be found in Appendix A of this report.

	Tudor Arches	*Trusses*
Glulam	7.96 kips	8.1 kips
Masonry	11.45 kips	15 kips
Total	19.4 kips	23.1 kips

Table 5. System dead load reactions, half of dead weight.

While the total weights are very similar, and slightly smaller for the new system, it is acknowledged that reducing the spacing of the arches increases the number of column bases so size reductions for the foundations are will not be a benefit of the design. More footings will be necessary, increasing the quantity of concrete needed over the entire building rather than reducing it.

Architectural Appearance

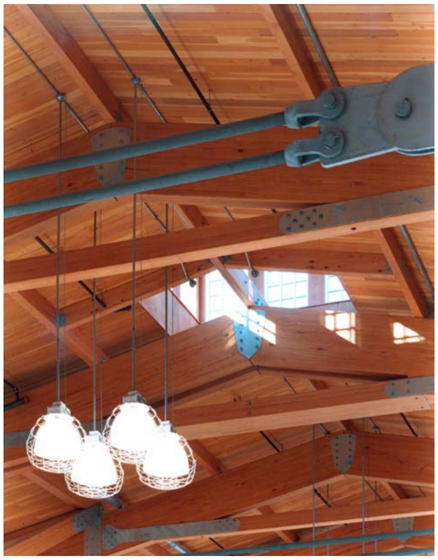


Figure 11. Truss bottom chords. Photo credit: www.som.com.

The main reason for designing of an alternative for the existing glulam trusses in the Brunswick School Athletic Building was to improve the aesthetics of the structure. The barn-like design of this building is very unique, especially the cedar plywood exterior and glulam roof framing. Sample photographs of the interior are shown throughout this report, courtesy of SOM's website. In Figure 11, the steel bottom chords of a truss are visible. Figure 6 shows the concrete piers on which the trusses bear. The grey piers contrast in color significantly with the brown tinted CMU. The three hinged arches would allow several improvements to the rink and court by eliminating the steel and the concrete piers. An altered building section with an arch instead of a truss is shown in Figure 12.

Also visible in Figure 12, however is the elimination of 2-3 feet of space along the wall at each frame, very detrimental to egress on the bench side of the rink where there is only 5 feet of clearance to begin with. This could be easily remedied by locating the rink 2-3 feet further from the south wall. The lessened space does not have any effect on the basketball court because the court does not come as close to the walls.

The redesign of the roof using Tudor arches would improve the appearance and barn style of the ice hockey rink and basketball court by eliminating color contrast in the walls the need for steel truss chords.

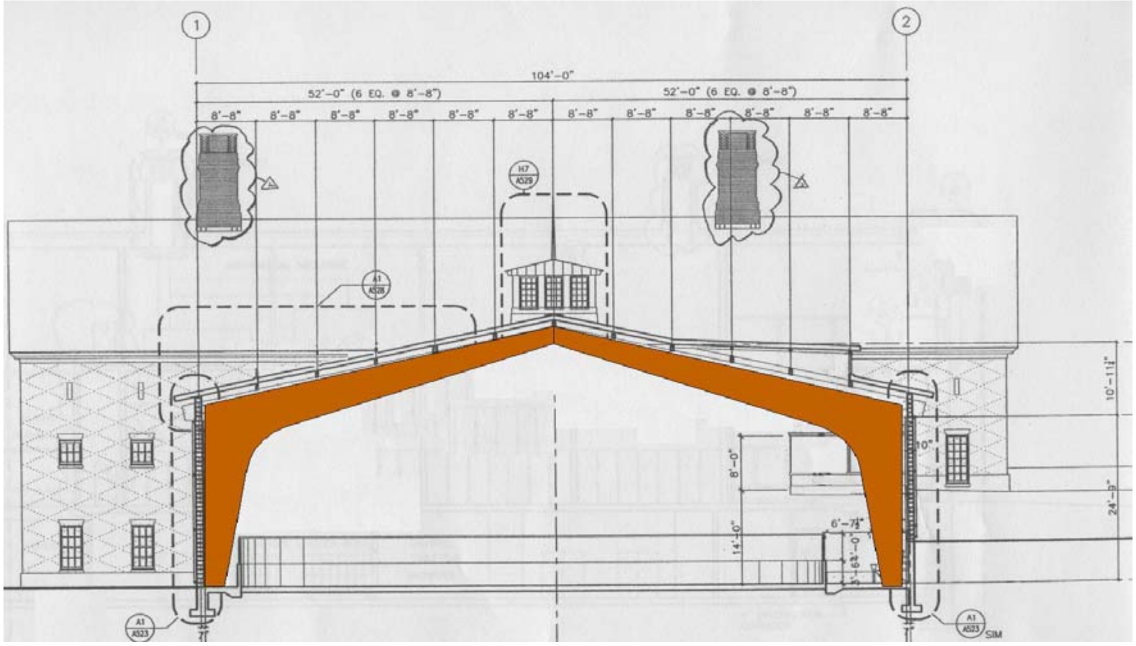


Figure 12. New building section showing Tudor arch.

Construction

Unadilla Laminated Products was the designer and manufacturer of the existing timber trusses and is a leading supplier of glulam framing for the northeast, as well as a member company of the AITC. Unadilla would be contracted to manufacture and deliver the designed timber frames. Figure 13, from www.unalam.com shows the unique manner in which they deliver their products to site. Shipping specifications for the 21’-4” frame are shown in Figure 14. These dimensions determine the roads that the truck can take to get from Unadilla, NY to Greenwich, CT.

Figure 13. Unadilla Laminated Products delivering one of their beams to a site.

Photo credit: www.unalam.com.

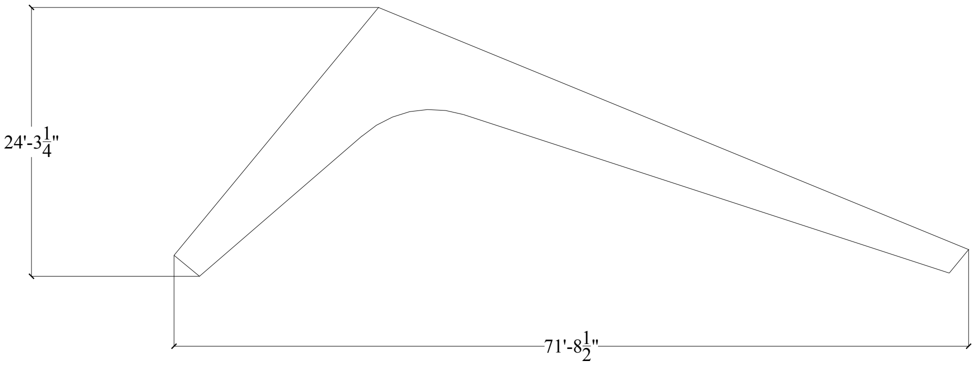


Figure 14. Shipping dimensions.

A detailed existing construction schedule was never attained because of the school's wishes to keep certain factors private. It was discovered, however, that the masonry contractor took extra time to complete their work and caused significant delay in the construction. For a school building that required project completion before the start of the school year, any extensions to the schedule caused problems. According to Turner, this project did in fact run over by one week and was finished the day before the new school year would begin. An excerpt from the estimated existing schedule is shown below.

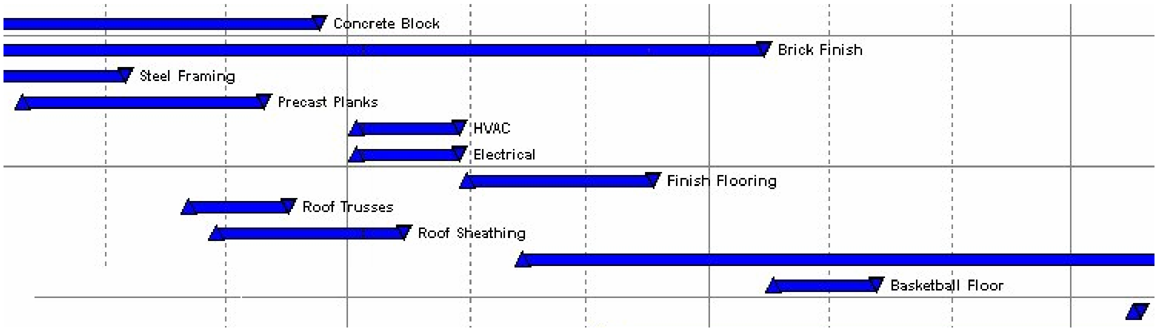


Figure 15. Part of existing schedule.

Use of the designed timber trusses would have greatly improved this construction schedule. The existing design required completion of the CMU walls and piers before the roof trusses could be craned into place and the roof constructed. Use of the Tudor arch system would move the masonry off the critical path and allow roof construction to begin many months before the walls are completed. The building would be closed earlier allowing interior finishes and other similar processes to begin sooner, potentially

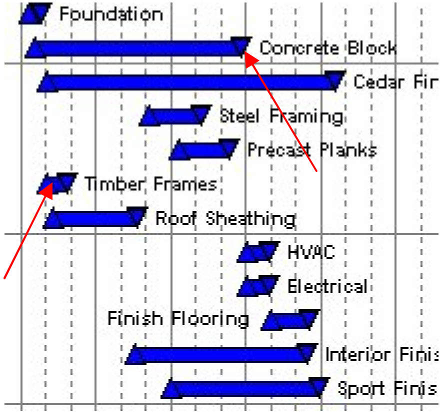


Figure 16. Excerpt from new schedule.

skimming months off the total construction time. An excerpt from the new estimated schedule is shown in Figure 16 with an arrows indicating the new time of roof framing in reference to masonry work. Please note that the scales of the two schedules are not equal; lengths of time remain the same for all activities, only the order and total time changes.

A school project with limited time would greatly benefit from the use of a new structural system with the potential to lower the total construction time by months.

Conclusions & Recommendations

Changing the roof system of the Brunswick School Athletic Building from glulam trusses to glulam Tudor arches offers many potential improvements to the aesthetics and construction time of the building. The original spacing cannot successfully be maintained, but 21’-4” and 20’-0” is relatively reasonable. While cost is not believed to be a large driving factor of the new Edwards campus of the school, construction time within the school year calendar and appearance to attract students are very important. It is recommended that for future designs of buildings similar to this one, the use of Tudor arches be considered.

Lighting Design

Existing Fixtures & Conditions

The existing lighting system above the ice hockey rink in the Brunswick School Athletic Building consists of 400 Watt Prismaline fixtures, like those in Figure 17, arranged in clusters of four. Specifications for these fixtures can be found in Appendix B. Review of the photos on SOM's website revealed many bright reflecting spots on the ice surface due to the clusters. These spots, as well as those produced by the dormer windows are indicated in Figure 6 along with the piers and the CMU wall. During a hockey game, these spots can be distracting to players following a puck causing disruption in play and potentially dangerous collisions.

Figure 17. Prismaline fixture used in existing layout. Credit: www.holophane.com

The proposed redesign of the rink lighting consisted of either changing the layout or the fixtures. Use of the Luxicon lighting program resulted in successful redesign of the layout so selection of new fixtures was not necessary.

Layout

The lighting requirements for such high school ice hockey rinks are specified in *The IESNA Lighting Handbook* as 50 foot candles at the ice surface. The fixtures are suspended at 29 feet above the ice surface between each truss. The uniqueness of this space affected the luminance, darker than usual ceiling materials, unpainted walls, and highly reflective ice. Also unique is the placement of the work plane at ground level, because that is where the puck, and therefore most of the focus would usually be. The calculation results and rendering in Figures 18 and 19 of the existing conditions clearly shows the bright spots, indicated with arrows. The calculation grid shows the luminance of the concentrated light spots at as much as 80 fc. An average luminance of 57.3 foot candles is produced by this arrangement.

Using Luxicon, the fixtures were spread out for the existing truss spacing, as well as the new arch spacing. The number or fixtures was reduced from 72 to 70, and an average luminance of 49.2 fc is produced. All surfaces of the ice are above the required 50 fc and, as shown in the following calculation results and rendering, Figures 20 and 21, for the new 20-22 foot spacing the bright spots are successfully eliminated and a much more evenly lit surface is produced. The ice surface receives a nearly constant luminance of 68-71 fc.

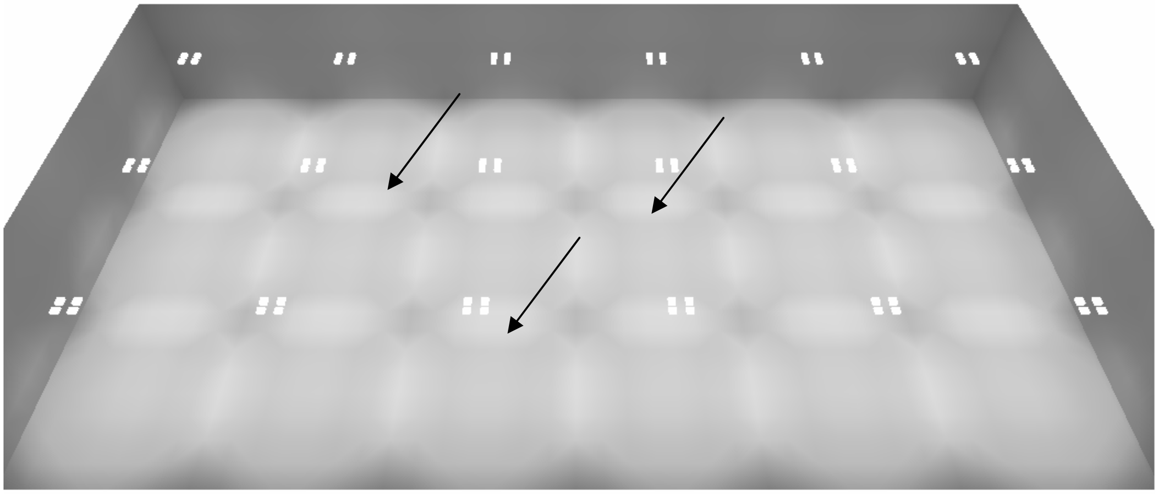


Figure 18. Rendering of existing layout.

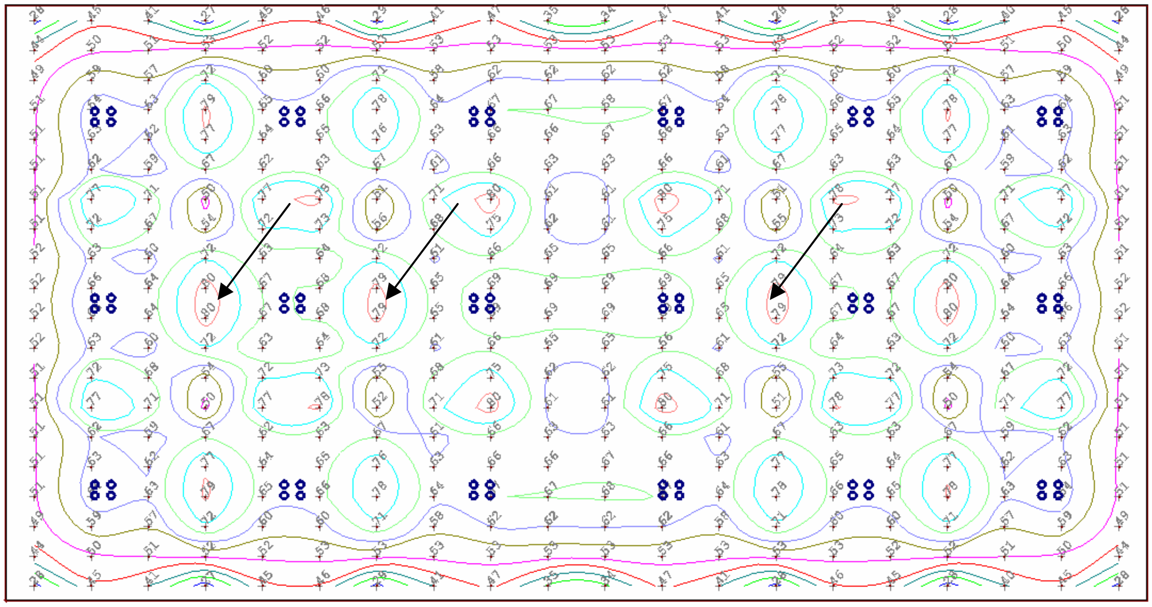


Figure 19. Calculation grid of existing layout.

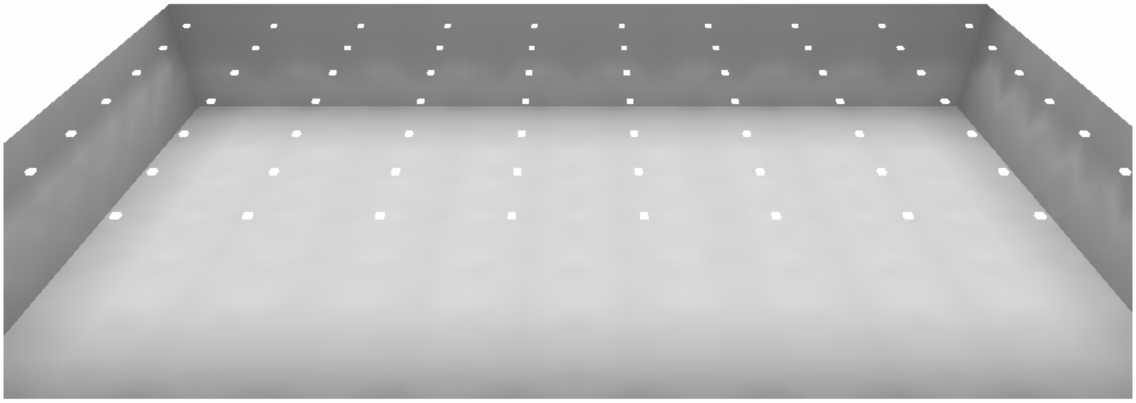


Figure 20. Rendering of new layout.

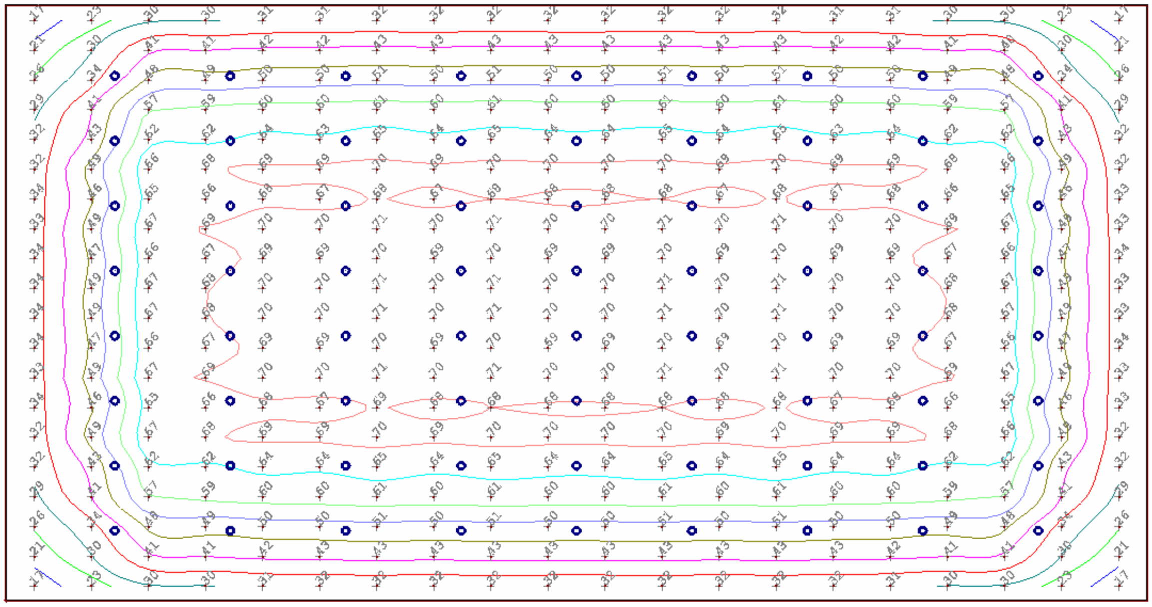


Figure 21. Calculation grid of new layout.

Windows

As undesirable as it usually is to eliminate day lighting in any space, the windows above the ice rink were eliminated from the structural design because they cause more problems to the lighting conditions than benefits. Windows similar to these at the Penn State Ice Rink were removed because they caused melted spots on the ice, according to Moses Ling. Considering the brightness of the glare in the photograph there is little doubt that these windows also could melt the ice surface, causing dangerous skating conditions for the young hockey players. In consolation, day lighting is used in other spaces of the building, including the entry foyer / trophy room on the second floor, as shown in Figure 22. The windows are not completely necessary to maintain the Shaker style architecture, as most dormer windows the Shakers used were not much more than a few feet across, rather than 55 feet as these are, so to eliminate the glare and melted ice the windows ought to be left out of the redesign.

Figure 22. Daylighting in trophy room / foyer. Photo credit: www.som.com.

Conclusions & Recommendations

To eliminate the distracting and potentially dangerous bright spots on the ice surface, the lighting layout should be spread out and the dormer windows removed. The layout described maintains the specified luminance while providing a more consistently lit surface.

Building Enclosure

Existing Wall Section

The walls of the ice rink and basketball court are of the same construction: twelve inch fully grouted CMU, a moisture barrier, rigid insulation and ½" of air covered with cedar plywood, as shown in Figure 23. The two spaces have very different interior temperatures and high relative humidities which hinted at the possibility of moisture collection within the cross section of at least one of the walls. Based on the following room and weather conditions, thermal and moisture gradients were developed.

	Winter	Summer	Interior, Ice Rink	Interior, Basketball Court
Temperature	-9 C	30 C	0 C	22 C
Relative Humidity	72 %	86 %	75 %	65 %

Table 6. Room and weather conditions.

Weather conditions were found at Accuweather.com and interior conditions were found in *ASHRAE Refrigeration*.

Enclosure Analysis

By summarizing the thermal resistance and vapor resistance values of each material, and dividing each proportionally over the wall section, the temperature and vapor pressure at each material can be determined. If the actual vapor pressure equals the saturation vapor pressure at any point, moisture will accumulate at the cold side of the material where saturation occurs. For the walls of the Athletic Building, the drawings were not specific to materials used and Specifications were not available. It was assumed that the moisture barrier such as Grace Construction Product's Bituthene and the insulation to be rigid fiberglass. Values of thermal and vapor resistance were obtained from *ASHRAE Fundamentals* and Grace's website. An example spreadsheet is shown below. All necessary spreadsheets are included in Appendix C of this report.

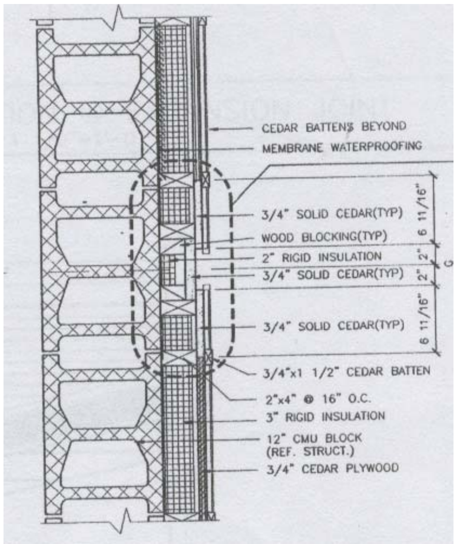
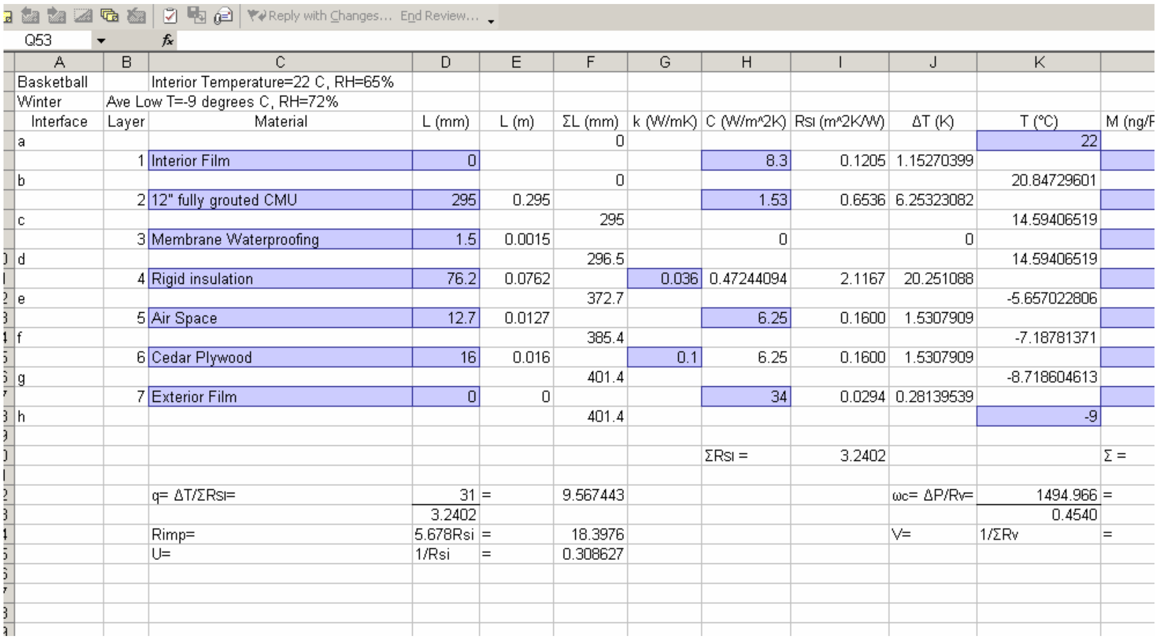


Figure 23. Typical wall section.



A	B	C	D	E	F	G	H	I	J	K	
Basketball		Interior Temperature=22 C, RH=65%									
Winter	Ave Low T=-9 degrees C, RH=72%										
Interface	Layer	Material	L (mm)	L (m)	ΣL (mm)	k (W/mK)	C (W/m^2K)	RSI (m^2K/W)	ΔT (K)	T (°C)	M (ng/
a					0					22	
	1	Interior Film	0				8.3	0.1205	1.15270399		
b					0					20.84729601	
	2	12" fully grouted CMU	295	0.295			1.53	0.6536	6.25323082		
c					295					14.59406519	
	3	Membrane Waterproofing	1.5	0.0015			0		0		
d					296.5					14.59406519	
	4	Rigid insulation	76.2	0.0762		0.036	0.47244094	2.1167	20.251088		
e					372.7					-5.657022806	
	5	Air Space	12.7	0.0127			6.25	0.1600	1.5307909		
f					385.4					-7.18781371	
	6	Cedar Plywood	16	0.016		0.1	6.25	0.1600	1.5307909		
g					401.4					-8.718604613	
	7	Exterior Film	0	0			34	0.0294	0.28139539		
h					401.4					-9	
							ΣRSI =	3.2402			Σ =
		q= ΔT/ΣRSI=	31	=	9.567443				ωc= ΔP/Rv=	1494.966	=
			3.2402							0.4540	
		Rimp=	5.678RSI	=	18.3976				V=	1/ΣRv	=
		U=	1/RSI	=	0.308627						

Figure 24. Screen shot of spreadsheet used to develop thermal and moisture gradients.

The winter conditions of each wall show dry performance, but the summer conditions have such a temperature contrast over the ice rink wall that moisture does in fact accumulate in the wall. As shown in the vapor gradient in Figure 25, however, the moisture will accumulate against the insulation where the intersection is circled, allowing it to drain from the wall. Provided that proper flashing is installed at the base of the wall, little to no problems should occur.

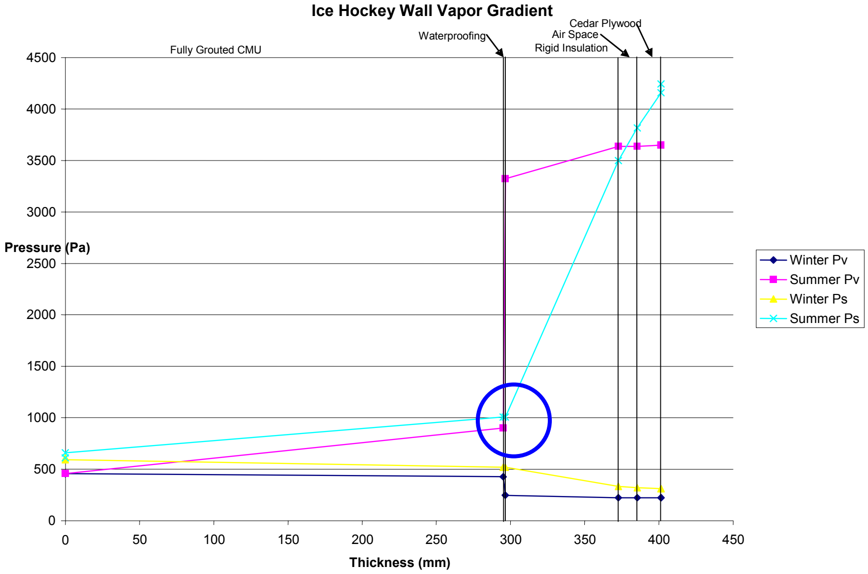


Figure 25. Ice hockey wall vapor gradient.

CMU Movement

The drawings of the existing walls include expansion joints only at re-entrant corners. It is assumed but never specified that joints were placed at each pier every 30-35 feet. The design for use of Tudor arches eliminates these piers, and thus the joints. Should spacing be reduced to 20-22 feet, joint must allow for less than ¼" of total movement due to CMU shrinkage and thermal expansion and contraction from a temperature variance of 50 degrees C. Joints accommodating for ¼" of movement should be installed at each arch.

Also necessary are supports for lateral movement of the wall. Ties between the CMU and arches should allow for some thermal movement of the block, but transfer lateral load and resist failure before the CMU walls are complete.

Conclusions & Recommendations

As suspected, the drastic variation in space temperatures in the basketball court and ice rink spaces that have the same wall construction, moisture does accumulate across the wall section. Luckily, the wall performs just fine, allowing the water to drain rather than causing problems. So long as flashing is provided to facilitate proper drainage, the enclosure of the Brunswick School Athletic Building will perform well.

If the new structural system is used, the CMU walls need expansion joints to allow for slight thermal expansion and CMU shrinkage. Placement should correspond with the spacing of the Tudor arches. Ties between the block walls and arches are necessary as well.

References

Design of Three-Hinged Arch, etc.

The American Forest and Paper Association, *National Design Specification® (NDS®) for Wood Construction, 2001 Edition*, and *Supplement: Design Values for Wood Construction*

American Institute of Timber Construction, www.aitc-glulam.org, 10/15/02.

American Institute of Timber Construction, *AITC Glulam Literature Binder*, includes *AITC 113-2001* and *AITC 117-2001*, March 2003.

American Institute of Timber Construction, *Technical Note 2: Deflection of Glued Laminated Timber Arches*, September 1998, aitctechnicalnote02.pdf.

American Institute of Timber Construction, *Technical Note 23: Mathematical Solution for the Design of a Three Hinged Arch*, September 1998.

American Institute of Timber Construction, *Timber Construction Manual, 4th Edition*, 1994, Chapter 5.13, Arches.

International Conference of Building Officials, *International Building Code, 2OOO.*

Linville, Jeff, AITC Technical Manager, email correspondence, Dec. 2001-March 2003.

Nicoletta, Julie and Morgan, Bret, *The Architecture of the Shakers*, The Countryman Press, Woodstock, Vermont, 1995.

Taly, Narendra, Ph. D., P. E., *Design of Reinforced Masonry Structures*, McGraw Hill, 2001.

Unadilla Laminated Products, www.unalam.com, 9/08/02.

Design of Lighting and Enclosure

Accuweather, www.accuweather.com, 3/18/03.

ASHRAE, *2002 ASHRAE Handbook: Fundamentals, 2002.*

ASHRAE, *2002 ASHRAE Handbook: Refrigeration, 2002.*

Burnett, Eric, Building Enclosures Text (Title unknown), 2003.

Grace Construction Products, www.na.graceconstruction.com, 3/18/03.

Illuminating Engineering Society of North America, *The IESNA Lighting Handbook, Reference & Application, 2000*.

Ling, Moses, PSU Architectural Engineering, personal correspondence, 3/17/03.

Acknowledgments

I would like to thank the following individuals for there valuable assistance in this Thesis:

The Penn State Architectural Engineering Faculty and Staff, especially:
- *Dr. Boothby*
- *Dr. Mistrick*
- *Moses Ling*
- *Kevin Parfitt*
- *Jonathan Dougherty*

Faculty from other departments, including:
- *Dr. Burnett of Civil and Architectural Engineering*
- *Dr. Manbeck of Agricultural and Biological Engineering*

Industry Professionals:
- *Jeff Linville and Holly Mais, The American Institute of Timber Construction*
- *Joe Dowd, Turner Construction*
- *Karl Chen and Gary Steficek, Gilsanz Murray Steficek, LLP*

My classmates for their infinite help and support, especially:
- *M y fellow 5th Year students:*
  - *Jaclyn Ambrocik*
  - *Megan Hawk*
  - *Rebecca Ho*
  - *Michelle Baldwin*
  - *Tracy Lo*
  - *Andrea Borowski*
- *Joseph Pinon, AE graduate student*

My favorite little sister and my friends, for maintaining my sanity:
- *Elissa, Carrie, Steve, Beth, Nellie, Laura, Curt, Nick, Lee, Jared and Ralph*

And most importantly, John, thank you for everything.